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Thermal analysis of the cold mass of the 2T solenoid for the PANDA detector at FAIR

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Abstract. The superconducting solenoid of the PANDA experiment at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt (Germany) is designed to provide a magnetic field of 2 T over a length of about 4 m in a bore of 1.9 m. To allow a warm target feed pipe oriented transversely to the solenoid axis and penetrating through the cryostat and solenoid cold mass, the magnet is split into 3 inter-connected coils fitted in a common support cylinder. During normal operation, cooling of the cold mass to the working temperature of 4.5 K will be achieved through the circulation by natural convection of two-phase helium in cooling pipes attached to the Al-alloy support cylinder. Pure aluminium strips acting as heat drains and glued to the inner surface of the three coils and thermally bonded to the cooling pipes allow minimizing the temperature gradient across the 6-layers coils. In this paper the thermal design of the cold mass during normal operation and current ramps up and down is validated using an analytical approximation and numerical simulation.

1. Introduction

The anti-Proton ANnihilations at DArmstadt (PANDA) is a fixed target spectrometer experiment envisaged for the future Facility for Antiproton and Ion Research currently under construction at FAIR/GSI, Darmstadt, Germany. The experiment aims at performing basic research on weak and strong interactions, exotic states of matter and the structure of hadrons.

At the core of the PANDA detector is the Target Spectrometer relying on a superconducting solenoid surrounding the interaction point [1-4]. The magnet features a warm bore of 1.9 m diameter and a free length of 4 m. Since the interaction point is located at 1/3 of the length of the winding, the coil is split at this location and the cryostat exhibits a warm bore of 100 mm diameter to allow the insertion of the target pipe. As a consequence, in order to balance the magnetic forces and guarantee the required magnetic field homogeneity ($2 \text{ T} \pm 2\%$ over the tracker region with an integral of the radial field component $< 2 \text{ mm}$), the solenoid is split into 3 sub-coils. The magnet system is completed by a flux return yoke composed of two end-cap

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doors and a barrel section laminated into 13 iron plates, which incorporate the mini-drift tubes for the muon detection.

Following collaboration with CERN, the original design of the PANDA solenoid [1-4] has been thoroughly revised in the last two years. This work has led to a number of significant and relevant changes including conductor dimensions, cold mass layout and coil winding procedure. In the following section the main modifications that are relevant for the thermal analysis of the magnet are briefly illustrated as needed to discuss and validate the thermal design of the PANDA solenoid.

2. Conductor shape and cold mass layout

The main driving reasons behind the push to modify the conductor design for the solenoid have been the necessity to increase the temperature margin to well above 2 K (original design value $\Delta T = 1.8$ K [1]) and reduce the height-to-width aspect ratio that would complicate both the conductor co-extrusion as well as the coil winding, thus increasing risk and production cost of the magnet. The main characteristics of the new conductor are summarized in Table 1. The modified design is a 10.9 x 7.9 mm Al-stabilized Rutherford cable composed of eight NbTi/Cu strands with 1.4 mm diameter and a Cu to nonCu ratio of 1.0. An additional advantage of a low height-to-width conductor is the reduction of the eddy current loss during current ramps as this is proportional to the width of the face of the conductor perpendicular to the magnetic field. In order to fulfil the magnetic field value and quality and coil geometry constraints, the solenoid is now wound in six layers. This could potentially lead to a higher temperature gradient across the winding pack as the thermal path from the cooling tubes, attached to the outer surface of the support cylinder, to the inner layer of the coil is now characterized by a higher thermal resistance (i.e. more inter-layer insulation).

Table 1. Summary of the main characteristics of the Al-stabilized Rutherford NbTi/Cu conductor for the PANDA solenoid.

Parameter	Value
Number of strands	8
Strand diameter (mm)	1.4
Filament diameter (μm)	20
Cu to nonCu ratio	1.0
Cable dimensions (mm)	2.6 x 5.3
Conductor bare dimensions (mm)	7.93 x 10.90
Insulation thickness (mm)	0.40
Temperature margin (K)	2.4

The cold mass layout has been modified taking advantage of the necessity to split the solenoid into three sub-coils. As a consequence, the cold mass, i.e. winding pack and support cylinder assembly, will be produced as three separate modules connected by flanges and inserted into a common cryostat, as illustrated in Figure 1. The envisaged winding procedure is outside winding of each coil on a collapsible mandrel, followed by resin impregnation and a shrink fit of the support cylinder. The new cold mass assembly layout and procedure allow simplifying the manufacturing hence lowering the production cost, and correction of eventual errors occurring during the winding process by insertion of shims between the coil modules. A

further change concerns the thickness of the support cylinder, which has been increased to a uniform value of 40 mm, except at the location of the flanges between different coil modules.

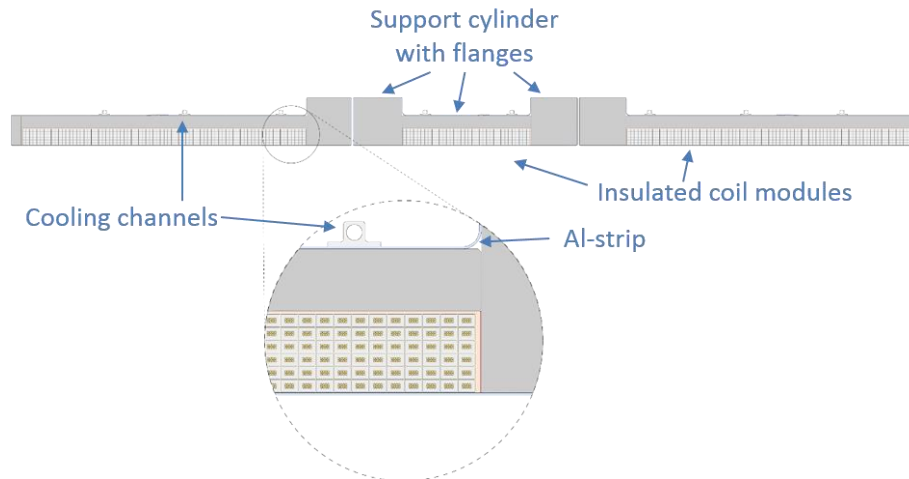


Figure 1. The PANDA solenoid will be wound as three separate coil modules connected through flanges. Each module will consist of a 6-layers coil and its support cylinder.

Finally, to sustain the larger weight of the cold mass and to reduce the shift of the magnetic centre following magnet energization, the cold mass support system has also been revised in terms of both material and number of the axial and radial rods.

All of the above changes imply variations of the heat loads to the cold mass and affect the thermal design of the PANDA solenoid, requiring a re-assessment.

3. Heat load to the cold mass and cooling scheme

In Table 2 the heat loads to the cold mass of the PANDA solenoid are summarized, specifying whether the loss is estimated analytically or through a Finite Element Model (FEM) [5]. The eddy current loss in the conductor is derived with a mixed method, i.e. by inserting the local magnetic field on each turn of the solenoid computed via a FEM, into the analytic loss expression given by Equation 1 [6], where h and d are the faces of the conductor parallel and perpendicular to the magnetic field B respectively, ρ is the Al-stabilizer resistivity and l is the length one turn of the coil. Magneto-resistivity is also taken into account.

$$P = \frac{lh}{12} \cdot \frac{d^3}{\rho} \left(\frac{dB}{dt} \right)^2 \quad (1)$$

Table 2. Summary of the heat loads on the cold mass of the PANDA solenoid.

Heat load component	Q (W)	Model details	Notes
Eddy current loss in casing	11.5	3D FEM	Current ramp time = 2000 s.
Eddy current loss in conductor	0.09	Mixed	Current ramp time = 2000 s.
Radiation	1.5	Analytic	[7], Thermal shield temperature = 60 K.
Residual gas	0.5	Analytic	[7], Operating pressure = 2e-6 mbar
Conduction through support system	2.8	Analytic	[7], 12 radial + 8 axial rods at 77 K, thermalized and 2/3 of their length.
Joint resistance	0.5	2D FEM	6 joints of 1 m length.

As expected from the low height-to-width ratio of the conductor, eddy current loss in the conductor is negligible especially when compared to the eddy current loss in the casing, which represent the main heat load component during current ramps. In steady-state operation, the largest load instead is the heat in-leak through the cold mass support system, composed by twelve radial and eight axial rods thermalized to the magnet shield at 77 K. Including additional 10 W from the cryogenic chimney and control dewar, the total heat load to the PANDA cold mass amounts to 54 W (with safety factor 2).

During normal operation, the cold mass of the PANDA solenoid cooled at the working temperature of 4.5 K through the circulation by natural convection of two-phase helium in cooling pipes attached to the support cylinder, as illustrated in Figure 2 [8]. The initial cool down of the magnet is achieved by forced flow He circulation, obtained by opening valve CV1 in Figure 2 and thus bypassing the 300 l tank in the control dewar. Cooling of the thermal shields to 40 – 80 K is carried out by the flow of pressurized He gas from the cold box. Finally, a fraction of the liquid He in the control dewar is used for cooling the superconducting current leads of the magnet.

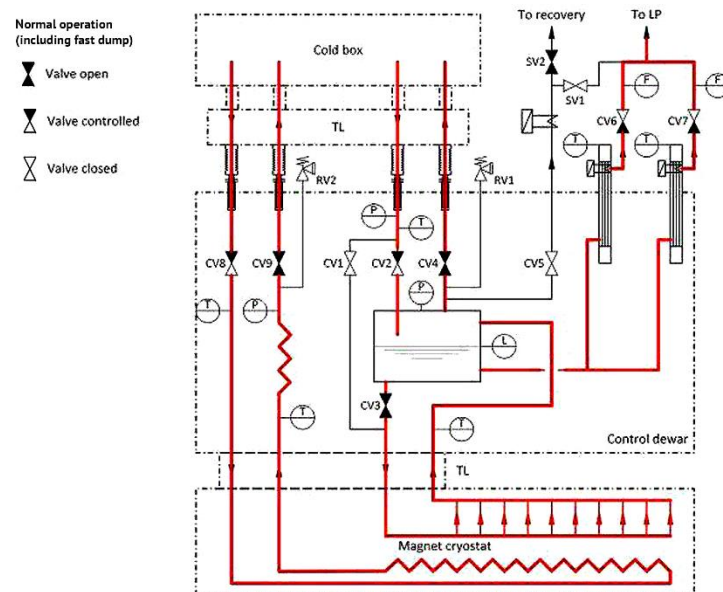


Figure 2. Cooling scheme of the PANDA solenoid by natural convection during normal operation [8].

In order to verify the feasibility of thermo-siphon cooling of the PANDA cold mass a preliminary assessment of the expected mass flow rate and vapor fraction has been performed using a simplified version of the homogenous model described in [9-11]. In the model, the quantities of interest are determined by balancing the driving hydrostatic pressure difference, which results from the thermally induced density gradient between the hot and cold sides of the loop, with the fluid acceleration and friction pressure drops in the supply and return tubes. Pressure drop at singularities and the difference between outflow and liquid level in the dewar are neglected in the present calculation. The main parameters of the thermo-siphon cooling circuit are illustrated in Figure 3. The system consists of a bottom supply and top return

manifolds running along the length of the cold mass and 16 siphon tubes (\varnothing 10 mm) welded on the two halves of the support cylinder. \varnothing 25 mm lines connect the top manifold with the control dewar located approximately 2 m above the cold mass. Using these parameters the expected mass flow rate is $\dot{m} = 110$ g/s, with a vapor fraction $< 3\%$, which is well below the generally accepted limit of 10% for successful thermo-siphon operation [9-11]. The model thus confirms that the height of the control dewar with respect to the bottom of the magnet, which is limited by a concrete radiation protection wall located above the PANDA detector, is sufficient to guarantee the driving hydrostatic pressure. The thermo-siphon tubes and supply/return lines are also properly dimensioned to guarantee minimal pressure drop along the cooling circuit.

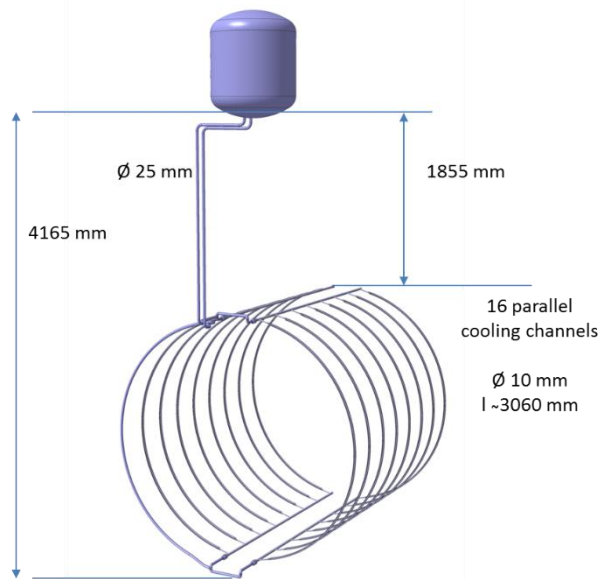


Figure 3. Thermo-siphon circuit of the PANDA solenoid.

The cooling scheme of the PANDA solenoid is completed by pure aluminum strips acting as heat drains and glued to the inner surface of the coils and thermally bonded to the cooling pipes. Due to their large thermal conductivity, the strips will provide a low thermal resistance path from the cooling tubes to the inner layers of the winding pack, allowing a reduction of the temperature gradients across the 6-layers coils. As shown in Figure 1, the strips will be routed around each coil, thus taking advantage of the modular approach adopted in the cold mass assembly in order to reduce the length of the thermal path and provide more effective cooling.

4. Validation of the thermal design

In order to validate the thermal design of the PANDA solenoid a $\frac{1}{4}$ symmetry 3D model of a cold mass module, i.e. winding pack and its support cylinder, has been created in Ansys® [5]. Due to the modular assembly of the cold mass, the coil modules will be separated by shims inserted between the connecting flanges. Therefore, as a first approximation, it is possible to assume them as thermally decoupled. The analysis is conducted on the upstream coil module since it is subjected to the highest heat load of the three as it features both axial and radial supports.

The model includes inter-turn and ground insulation, axial and radial supports, the Al-5083 coil casing and the aluminium strips. The turns of the coil are individually modelled, but for the

thermal analysis they are assumed to be made of pure aluminium. The thermal conductivity of pure aluminium for both strips and conductor is conservatively evaluated for a RRR of 500 (design value RRR = 1000) in 3 T magnetic field, corresponding to the peak field on the conductor. The cooling pipes are assumed to have a fixed temperature of 4.5 K. The azimuthal position of the Al-strips is determined by the location of the axial and radial supports as well as of the holes for the bolts in the flange connecting the upstream and centre coil modules (not included in the model).

As detailed in Table 3, four thermal designs are compared in the analysis. Design 1 in Figure 4a corresponds to the basic configuration where each cold mass module is cooled by two cooling pipes located on the support cylinder close to the edges of the coil and two Al-strips are routed between the cooling tubes at the inner surface of the winding pack. In Design 2, a third cooling pipe is added at the centre of the coil. In Design 3, the coverage of the Al-strip is extended between the two cooling tubes at the outer surface of the cold mass. Finally, Design 4 includes both upgrades, i.e. three cooling pipes and Al-strips at the inner and outer surfaces of the module, see Figure 4b.

Table 3. Summary of the analysed designs for the PANDA cold mass.

Design	Number of cooling tubes	Al-strip position	T_{peak} conductor (K)
1	2	Inner surface	5.03
2	3	Inner surface	4.92
3	2	Inner & outer surfaces	4.90
4	3	Inner & outer surfaces	4.90

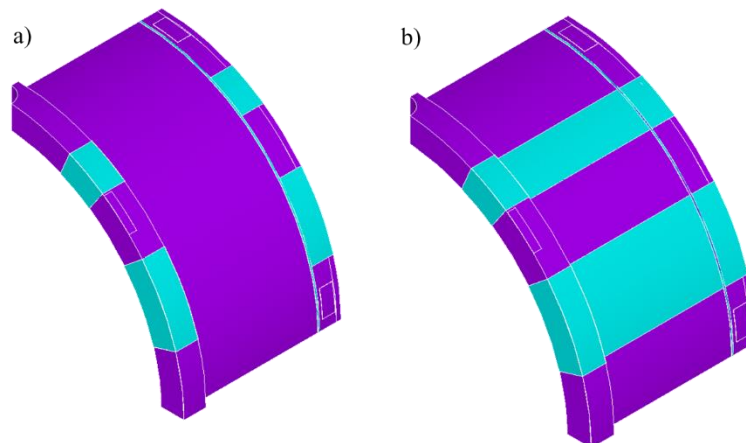


Figure 4. View of the FE model corresponding to Design 1 (a) and Design 3 (b). The different routing of the Al-strips in the two cases, only at the inner surface and at both inner and outer surface of the cold mass module respectively, can be distinguished.

The peak temperature on the conductor in the four cases is reported in Table 3. The maximum value is 5.0 K in Design 1, which is only 0.5 K above the operating temperature. The peak temperature on the conductors is localized in correspondence with the radial support connections, i.e. at the corner conductors in the outer layer of the coil. Considering that at this position the magnetic field is well below the peak value of 3 T used for the definition of the temperature margin, the reduction of ΔT for the PANDA solenoid in steady-state and current

ramp operations appears to be minimal even with the basic cooling tubes and Al-strips layout of Design 1. Moreover it should be noted that the peak temperature is likely overestimated because the model assumes perfect thermal contact between the support rods and the cold mass, while in reality the heat transfer is limited at the mechanical interface.

Figure 5 shows the temperature distribution in the analyzed module for the four different designs. It can be noticed that the extension of the Al-strip to the outer surface of the cold mass is a very efficient way to reduce the temperature of the conductors. In fact the addition of a third cooling pipe in Design 2 decreases the temperature of the conductors in the inner layers of the coil by approximately 0.1 K compared to Design 1. On the other hand, the reduction is of the order of 0.25 K in Design 3. An additional advantage of the Al-strip heat drains is that their installation requires significantly less work compared to the production and assembly of an extra cooling tube.

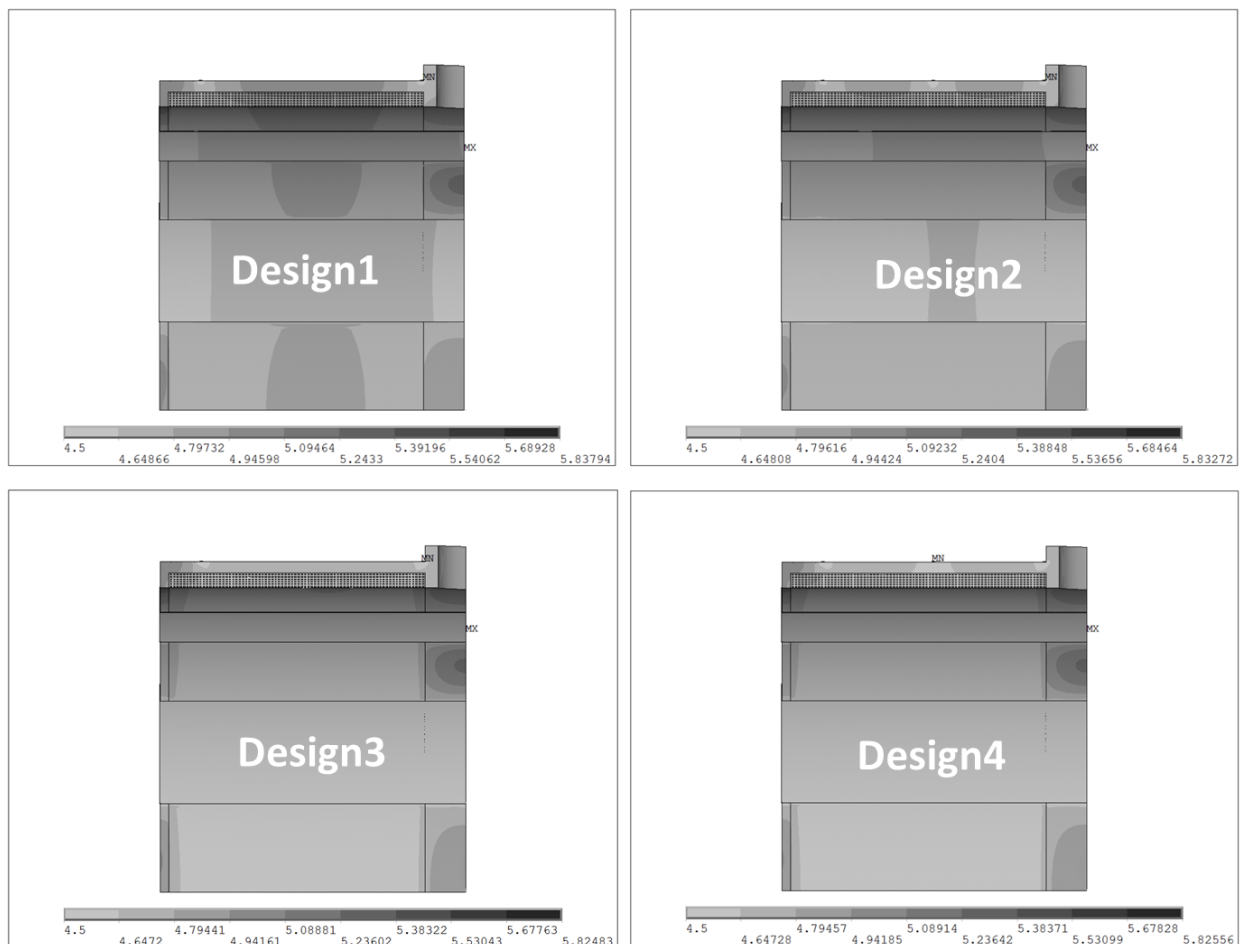


Figure 5. Temperature distribution in the upstream module of the PANDA solenoid cold mass for the four analyzed thermal designs.

5. Conclusion

Following the changes applied to the design of the cold mass and its support system in the last two years, the heat load of the PANDA solenoid has been re-assessed. The analysis shows that no significant variation of the overall heat load has occurred compared to the design proposed

in the Technical Design Report of 2009. Moreover, the possibility to cool down the magnet during normal operation by natural convection has been confirmed. Thermo-siphon offers the advantage of being a self-regulating process and not requiring mechanical components that could potentially fail. It is also verified that the presence of temperature gradients across the 6-layer coils can be effectively reduced by gluing pure Al heat drain strips at the inner surface of the magnet and thermally bridging them to the cooling tubes. Although two cooling tubes at the edge of each coil and Al-strips only at the inner surface of the coil would be sufficient to guarantee minimal reduction of the temperature margin during current ramps, routing of the strip also on the outer surface and the addition of an extra central cooling pipe for the longer upstream and downstream coils will be implemented in order to improve the operational margin and reliability of the thermal design of the PANDA solenoid.

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